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ORBITING DYNAMIC COMPRESSION LABORATORY

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I. Abstract

In order to examine the feasibility of carrying out dynamic compression experiments on a space station the possibility of using explosive gun launchers was briefly studied. Major emphasis, however, was put on examining the question of whether powders of a refractory metal (molybdenum) and a metallic glass could be well consolidated by dynamic compression. In both cases extremely good bonds were obtained between grains of metal and metallic glass at 180 and 80 kb, respectively. When the oxide surface was reduced and the dynamic consolidation was carried out in vacuum, in the case of molybdenum, tensile tests of the recovered samples demonstrated beneficial ultimate tensile strengths of 0.8 GPa (110 ksi).

II. Introduction

The operation of a dynamic compression laboratory in space would make it possible to extend present high pressure shock wave experiments by nearly an order of magnitude higher in pressure, and provide one or two orders of magnitude greater precision in our knowledge of condensed media. A whole new class of dynamic isentropic compression experiments appear to be feasible in the space environment. Critical to the conduct of such science from a space station is the presence of high quality vacuum and the relative ease of using cryogenics in the (space) environment, as well as a capability, yet to be developed, for recovering large quantities of shocked and isentropically compressed materials.

We have proposed two concepts which can be used to carry out impact and dynamic compression experiments in space. These are the opposed orbit impact configuration and the use of long, but low-mass, structures in the form of a series of explosive guns.

The colliding orbit system stems from the ability of the shuttle system to place in either polar orbit, or, orbits inclined with respect to the equator, impact laboratories (which are presumably part of the proposed space station). These could be in approximately opposing polar orbit or 180° out of phase in inclined equatorial orbits. Probably the simplest visualization of the colliding orbit concept is shown in Figure 1 for the case of circular orbit. This would yield net impact velocities of 15 km/sec and a range of shock pressures up to 20 Mbar (Figure 2). Colliding objects in inclined equatorial orbits, such as launchable from Cape Canaveral, would still yield relative impact velocities significantly higher than currently available in terrestrial laboratories without losing the advantage of space-based experiments. However, it appears that polar orbits are optimum for colliding impact experiments. The colliding orbit, high-speed interaction is achieved, for example, by having transponders on the impact

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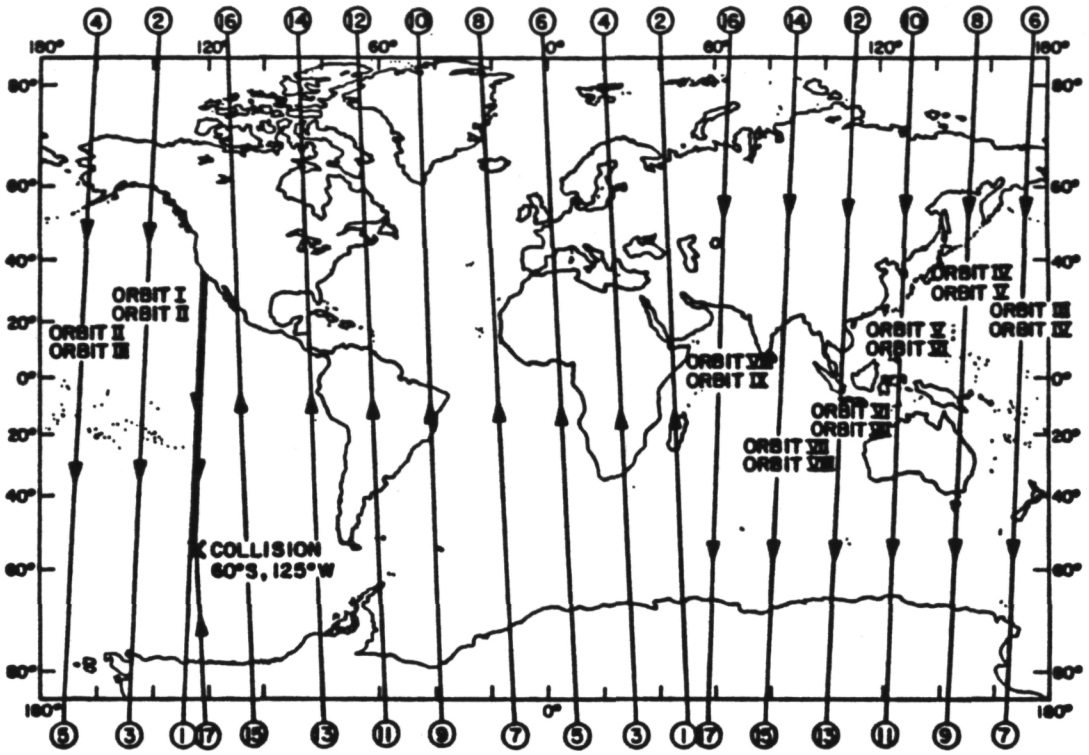

Fig. 1. Ground track of vehicle launched due south from Vandenburg AFB, into 100 nautical mile elevation polar orbit, demonstrating how a second vehicle launched 8.16 orbits after first vehicle will give rise to a collision over 60°S, 125°W.

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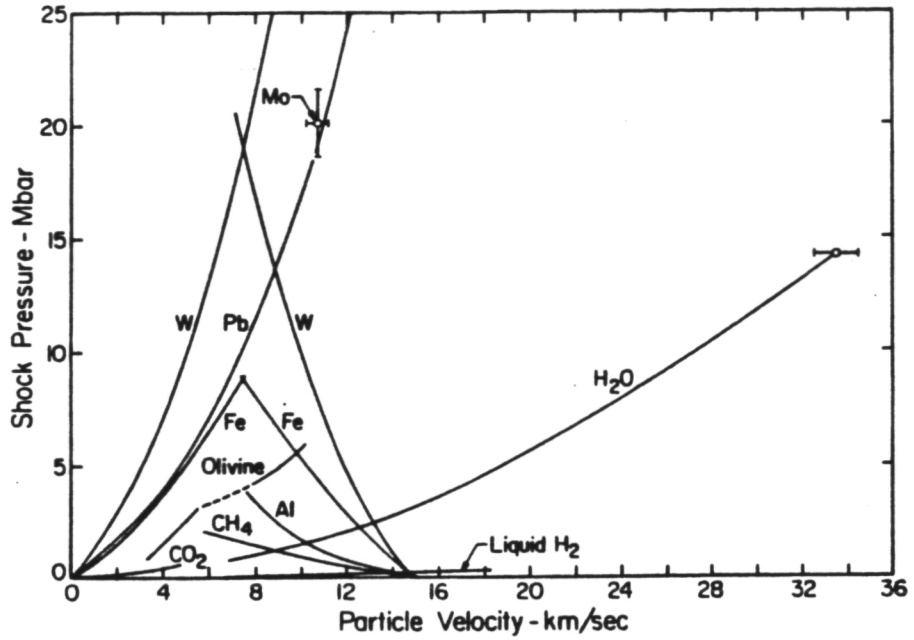

Fig. 2. Pressure-particle velocity plane for various materials, impacting at 15 km/sec. Shock pressure found by intersection of pressure-particle velocity curves, centered at 0 and 15 km/sec, e.g., ~19 Mbar for W impacting W; ~13.6 Mbar for W impacting Pb; 1.6 Mbar for Al impacting H_2O. Specific data for Mo and H_2O, with experimental errors shown, are from Ragan et al. (1977) and Podurets et al. (1972), both obtained using nuclear explosives. As can be seen from the figure, by choosing impactors and target materials a wide range of very high pressures may be achieved via a single available impact velocity.

laboratory portion of the space station orbiting the earth in one direction and presumably a small onboard microprocessor and very high speed thrusters and sensing systems on the impact dispenser or impactors themselves. Planar and very direct impacts are achievable with present technology for even "uncooperative" targets. We envision impactors similar in shape (but very much larger, and travelling about twice the relative speed) to those being presently used in terrestrial shock-wave laboratories. (Fragment hazards can be eliminated via methods used in terrestrial laboratories.)

The second concept, which we have carried out some exploration of under the present project, is the use of explosive guns for launching high-speed projectiles for scientific purposes. Research and development of such apparatus went through an intense period in the 1960's in the United States (Cable, 1970), and more recently, a series of impressive studies have been carried out in the Soviet Union (e.g. Urushkin et al, 1977). As apparent in Figure 3 these devices require the safe handling of large quantities of explosives. Isolation from explosive gas blast and the use of a great amount of physical space are problems with these devices on earth. Because of the extensive vacuum and physical support and alignment requirements, these devices could for the present application be easier to use in space.

Although much computation research could be carried out in an attempt to describe such devices, we have instead sought to gain some experience in constructing and operating a small version of such an apparatus. Under the present program we started to build such a device but have not yet fired it. (Section III-B.). We also proposed to examine the question of whether it was possible to shock compact powders and make them into useful materials in a space orbiting dynamic compaction laboratory. We chose to study two materials for which impact experiments had not yet produced really good consolidation, pure

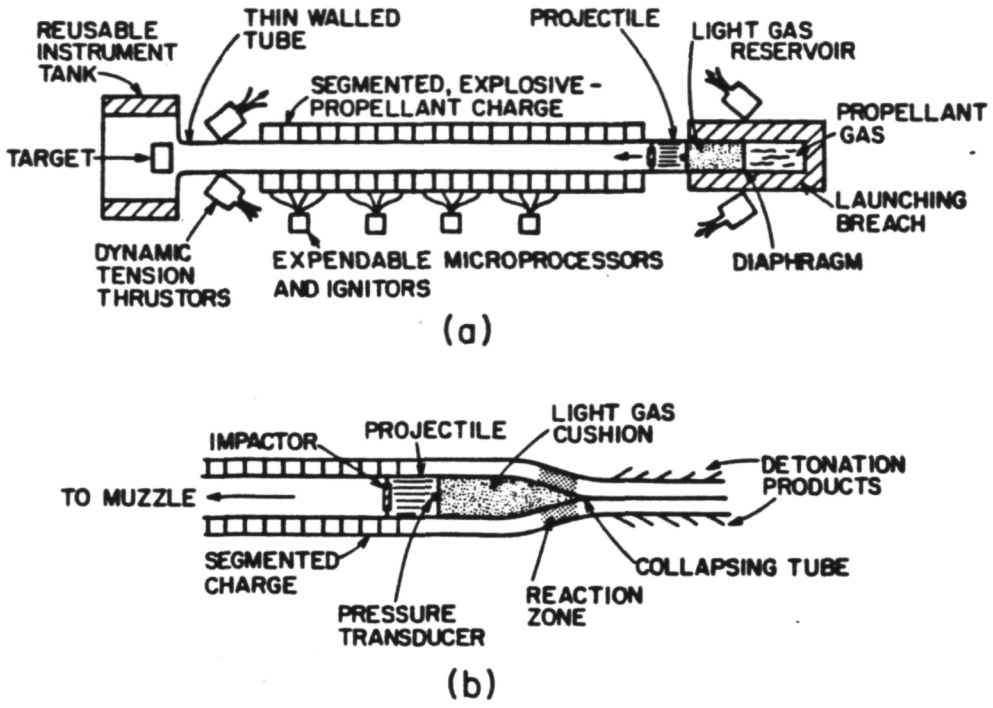

Fig. 3. Hypothetical configuration of light weight explosive gun for dynamic compression experiments in space.

(a) Configuration prior to launch.

(b) Segmented charge is detonated by microprocessor which monitors projectile base pressure, position and velocity as acceleration occurs along dynamically stretched low mass tube.

molybdenum, and a non-ferrous metallic glass. We achieved extremely promising and possibly technologically useful results in this effort. (Section III-A). Finally we sought To examine the question of whether it was possible to recover shock compressed $MgSiO_3$ from impacts at 2 1/2 km/sec, and in the process, synthesize the high pressure garnet or perovskite structure of this material. Although we successfully recovered two samples of this material, they have not yet been analyzed in detail. The experiments are discussed in Section III-C.

III. Results

A. Impact compaction of refractory metals and metallic glass.

Both in the case of refractory metals such as molybdenum and in high performance metallic glasses such as Marko 1064 (Ni_{56}, Mo_{26}, Cr_{10}, and B_{09}) the technology for forming solid pieces from rapidly solidified powders is an active area of current research in materials science.

Shock wave consolidation is an attractive method for producing bulk solids which have metastable properties of the initial powder. The passage of the shock front compresses the powder to full crystal density while preferentially heating the surfaces of the powder particles. This heating may be sufficient in some cases to cause melting of the surfaces while leaving the particle interiors relatively cool. Hence after the passage of the shock front, the molten or extremely hot surfaces can be rapidly quenched by the particle interiors. Depending on the amount of surface melting, the quenching rates my be as high as $10^5 - 10^{10}$ ° C/s. Thus amorphous powders may potentially be welded together to form large amorphous solids with the use of shock waves.

Although details of the mechanisms by which the shock wave preferentially deposits energy have not been studied in detail, the deposition is probably accomplished by heavy plastic deformation and interparticle friction during the shock rise time. Since shock rise times can be as short as ten of nanoseconds, the heating is very short duration in nature.

Most previous shock wave consolidation of powders was accomplished either by detonating explosives attached to the powder, or by high-velocity impact of plates. Cline and Hopper (1977) first used explosives to weld or clad $Ni_{40}Fe_{40}B_{20}$ powder into a dense rod whose exterior was still amorphous. Morris recently (1982) used high-velocity flyers to compact Metglas 2826 ($Nb_{40}Fe_{40}P_{14}B_6$) amorphous alloy. Recently Murr et al, (1983) has reported some optical and electron

microscopy and hardness of shock compacted Mo. They discovered that explosively compacted (and hardened) Mo retained in excess of 300 diamond pyramid hardness (DPH) at high temperatures.

Our work on both the molybdenum and metallic glass provides a definitive demonstration that strong bonding between particles can be achieved upon shocking in vacuum.

Table 1 contains a summary of the results for the metallic glass from the present study. The recovered compacts had densities of 8.88 $\pm$ 0.17g/ cm^3. This is close to the crystal density of 8.96 g/ cm^3. Thus within the uncertainty of the measurements, total densification of the powder was achieved for the shock pressures and energies used in the present study. The unshocked material is shown in Fig. 4 & 5.

The compacts consolidated at the lower shock energies etched easily with 50 percent Nital etch (50%HNO_3 + 50% ethanol by volume) and revealed very clearly the interparticle boundaries as shown in Fig. 6. However, between the shock energy of 400 and 450 Kj/Kg, distinct transition occurs. The compacts with shock energy deposition above the 400 Kj/Kg no longer etched with 50 percent Nital, and x-ray scans showed substantial crystallization. A new etchant composed of 20% HF and 80% HNO_3 by volume with a trace of Si was found to reveal interparticle boundaries in the crystallized compacts, as shown in Fig. 6. However, boundaries are not as distinct and clear as in the amorphous compacts.

Marko 1064 is initially amorphous. Differential thermal analysis, microstructural observations of polished and etched powder before and after thermal treatments, and X-ray diffractometry indicate an amorphous to microcrystalline transformation occurs near 600°C. The amorphous phase shows no discernable etching in 20 min. Table I gives the experimental parameters together with a

Fig. 4. Unshocked Marko 1064 metallic glass powder. Reflected light photograph, 250X.

Fig. 5. Unshocked Marko 1064 metallic glass powder. SEM photograph, 200X.

Fig. 6. Marko 1064 metallic glass shock consolidated at 40 kilobars. Magnification 250X.

Table 1. Shock consolidation data on Markomet 1064 amorphous powder.

Initial Powder Density (gm/cm^3)	304 S.S Projectile Velocity ($mm/\mu s$)	Calculated Shock Pressure (GPa)	Calculated Shock Energy (KJ/Kg)	Is consolidated sample still amorphous
4.9 ± .3	.881 ± .017	4.9 ± .5	220 ± 20	Yes
4.7	1.18	7.6	380	Yes
4.9	1.28	8.9	400	Yes
4.5	1.26	8.2	450	No
4.9	1.39	10.5	480	No
4.37	-	4.0	230	Yes
4.44	-	7.7	430	Yes
4.57	-	12.0	630	No

summary of microstructural observations.

At the lowest shock energy only isolated particles or portions of particles show transformation to the microcrystalline phase, in amounts too small to detect in diffractometer scans. The amount of material transformed to the microcrystalline phase increases with increasing shock energy, and the highest shock energy produced a mostly microcrystalline compact with many macro bubbles. Softening at the highest shock energy may be attributed to grain growth and possibly to coarsening of boron precipitates.

In the case of molybdenum, aliquots of powdered Mo, -325 mesh (grains <45μm) (Figs. 7 & 8) were pressed into stainless steel sample containers to a density of 0.5 to .7 times crystal density or 6 to 7.3 gm/ cm^3. The samples were evacuated to <50μm Hg (air pressure) and impacted with 304 stainless steel projectiles.

In these experiments (Table II) shock energies in the range 185 to 894 kJ/kg failed to produce well bonded compacts of the as-received powder. An X-ray diffractometer scan of recovered fragments of a compact indicated the presence of tetragonal MoO_2 and suggested a possible problem with surface oxides and oxidation during the consolidation. The powder was treated at 750°C in an atmosphere of H_2 (dew point −60°C) for 4 h and loaded into a target assembly under an Ar atmosphere. After a 1 minute exposure to air, the target assembly was filled with Ar and the pressure reduced to 40μmHg. A shock of E = 580 kJ/kg produced a compact with the excellent microstructure shown in Fig. 9 (m=1.67, P_1 = 17.8 GPa). The hardness of the compact was measured to be comparable to that of the powder (DPH(5g) = 249). Tensile tests on the consolidated Mo gave a UTS of 0.76 GPa (110 ksi) which is comparable to rolled sheet or bar stock.

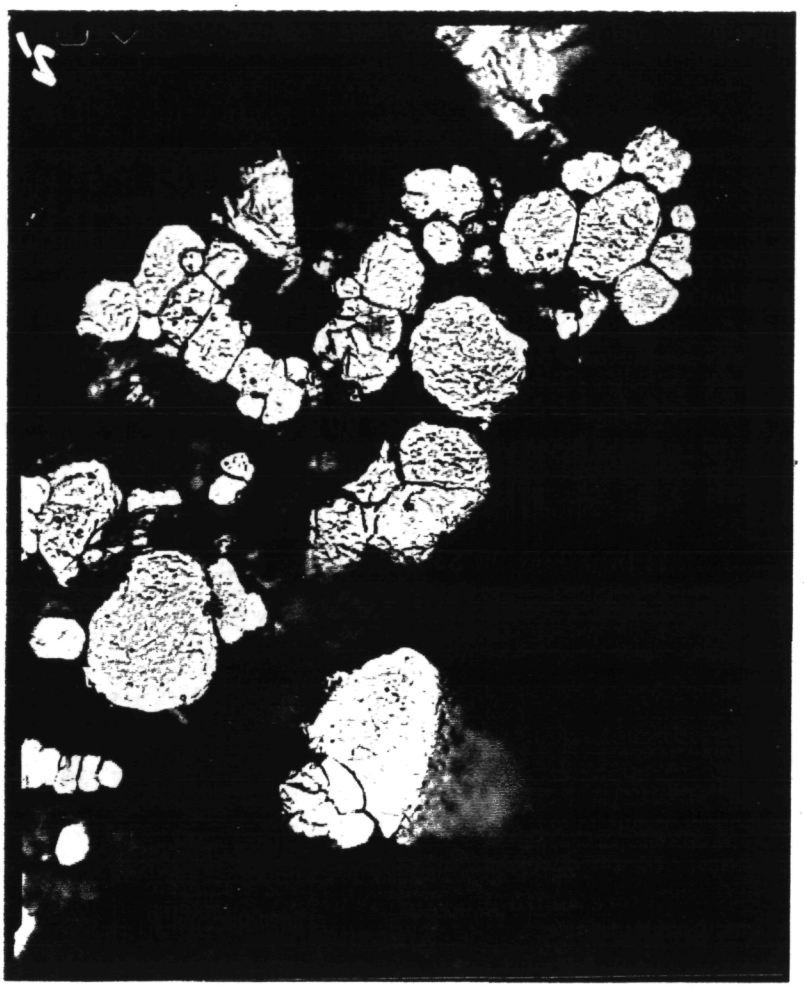

Fig. 7. Unshocked molybdenum powder. Reflected light photograph of etched material. Magnification, 1000.

Fig. 8. Unshocked molybdenum powder, SEM photograph, 250X.

Table 2. Shock recovery experiments, powdered Mo.

Initial Shock Pressure in Sample (GPa)	Diamond Pyramid Hardness	Initial Density (g/cm^3)
8.8	389	7.25
10.2	398	7.25
11.8	333	7.25
17.8	249	6.08

Fig. 9. Shock compacted molybdenum powder. Reflected light photograph 1000X (178 kbar). Material was exposed to H_2 atmosphere at 750°C before shock compaction in vacuum.

We believe we have developed a new technology for preparing solid molybdenum material which the results of Murr et al, (1983) on less consolidated materials, suggest has superior high temperature hardness and possibly other desirable properties. We conclude that surface oxide for both the metallic glass and molybdenum adversely affect interparticle shock bonding and this problem may be over come with reduction of oxides and shock compaction in vacuum.

B. Explosive Gun Feasibility.

Present terrestrial guns are limited to speeds of ~8 km/sec (using two stage light gas gun methods, (Cable 1970)) for acceleration of projectiles with mass of ~ 1gm or greater. There is a need for experiments to study dynamic equation of state, properties of materials by impact at greater speeds in the United States. In contrast Soviet workers have used explosive acceleration to launch projectiles to speeds of 15 km/sec since 1958 (Altshuler et al., 1958). This technology probably uses massive amount of explosives and it may be that significant improvements on explosive gun technology can be evolved using high speed electronic technology for initiation of multiple explosive charges. In addition to the high pressure equation of state area, there have been no experimental tests of the extensive studies of impact cratering mechanics that have been carried out in support of the U.S. program of studying impact processes on planetary surfaces.

Virtually no experimental impacts studies have speed greater than 8 km/sec have been carried out except on a very microscopic scale. This is a physical regime in which shock induced vaporization occurs extensively and condensation of the vapor has only been described theoretically. Condensation of the vapor, particularly for large inspects on the earth, for which the minimum impact velocity is 11 km/sec, appear likely to have caused a global dust layer (Alvarez et al., 1980). Experiments are required to test theoretical models of

impact vaporization

Although rail gun research in the U.S. and elsewhere (e.g. Hawke et al 1983) have sought to improve other acceleration technologies an apparatus to launch gm projectiles to speeds significantly above 8 km/sec has not yet been developed.

To gain some experience so as to carry out such explosive accelerations in a terrestrial laboratory and possibly in the future in a space environment, we sought to gain some experience with the techniques pioneered by Titov and co-workers (Titov et al, 1968, Urushkin et al, 1976, Lobanov & Fadeenko, 1979, and Titov & Shvetsov, (T&S), 1969). The latter authors have devised a high performance low explosive yield gun charge shown in Fig. 10. According to T&S the apparatus shown can accelerate a projectile, such as a 1mm steel sphere to 7.3 ± .25 km/sec . Using the technique sketched in Fig. 3 we believe we can strongly improve on this type of apparatus using multiple charge initiation. We have just acquired the explosive components shown in Fig. 10 at the time this project expired. The thickness of the charge which we expect to use with this explosive gun configuration produces a gas jet which accelerates the projectile. The charge thickness is just sufficient to sustain detonation of a liquid explosive such as TNM. However to obtain performance comparable with Soviet workers who use solid explosives the new explosive FEFO (Table 3) can be used. This material (methylenebis, oxybis, fluoro di nitro ethane) has a detonation pressure of 250 kbars much higher than the 144 kbars of tetranitromethane (TNM), and is comparable in performance to the high performance military explosives. (Table 3.) We believe that large light weight structures containing such a liquid explosive could be build in space. Experience should first be gained in explosive acceleration to determine how viable it is as a tool for carrying out dynamic compression experiments and impact cratering experiments. Experience with

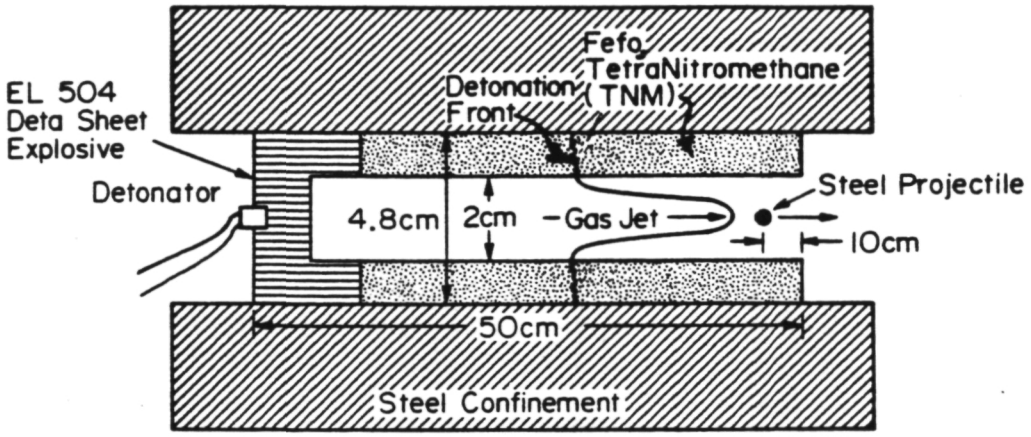

Fig. 10. Diagram of CIT version of explosive gun capable of launching 1 mm iron projectile to 7.3 km/sec.

Table 3. Liquid explosives possibly useful for explosive guns.

Explosive type	Density (g/cm^3)	Confined critical diameter (mm)	Chapman-Jouget pressure (kbar)
DEGN	1.38	6.76	-
FEFO	1.607	7.50	250
LX-01	1.24	6.84	156
MEN-I	1.02	5.49	(113)
NG	1.60	7.70	253
NM	1.13	6.35	125
TNM	1.6	6.4	(144)

safe handling of this kind of assembly will be vital if it is ever to be used in a space environment.

C. Shock Recovery Experiments on Enstatite.

In order to determine if we could recover material from higher velocity impact than previous experiments, we carried out two recovery experiments with impactors traveling at speeds of > 2 km/sec. The sample was enstatite which previous explosive loading experiments have demonstrated transforms with increasing pressure to a garnet and then a perovskite structure (Jakubith and Hornemann, 1981; Jakubith and Seidel, 1982). In both cases a fraction of the sample material was recovered (Table 4.) The results are promising and further analysis of the shock recovered material needs to be carried out.

Table 4. Enstatite Impact Recovery Experiments (Steel impactor and targets).

Sample #	Shot #	Velocity	Mass	Recovered Mass	Description
1	779	2.4±.1 km/s	22.0mg	<1mg	Recovered material was impregnated with steel from container. Attempted to separate steel from sample by using magnet in various solvents - H_2O acetone, alcohol. Only a few grains were separated and recovered. One grain shows a little birefringence and separate crystal domains. Analysis to be done: 1) Index of refraction of grain, 2) Gandolfi camera xray studies.
2	780	2.7±.1 km/s	27.0mg	∿3-5mg	Steel is mixed intimately with recovered sample. Birefringence is observed in some grains, though it is difficult to tell if the sample is contaminated. Analysis to be done: 1) Xray powder diffraction.

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